Oscillating Neutrinos from the Galactic Center

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ABSTRACT

It has recently been demonstrated that the γ-ray emission spectrum of the EGRET-identified, central Galactic source 2EG J1746-2852 can be well fitted by positing that these photons are generated by the decay of π^0's produced in p-p scattering at or near an energizing shock. Such scattering also produces charged pions which decay leptonically. The ratio of γ-rays to neutrinos generated by the central Galactic source may be accurately determined and a well-defined and potentially-measurable high energy neutrino flux at Earth is unavoidable. An opportunity, therefore, to detect neutrino oscillations over an unprecedented scale is offered by this source. In this paper we assess the prospects for such an observation with the generation of neutrino Čerenkov telescopes now in the planning stage. We determine that the next generation of detectors may well find an oscillation signature in the Galactic Center (GC) signal.

Subject headings: acceleration of particles — cosmic rays — elementary particles: neutrinos — Galaxy: center — galaxies: nuclei — radiation mechanisms: nonthermal — supernova remnants

1. Introduction

1.1. The Neutrino Source

The dominant radio emitting structures at the Galactic Center (GC) are the supernova remnant (SNR)-like shell Sagittarius (Sgr) A East, a three-armed spiral of ionized gas dubbed Sgr A West, and, embedded at the center of Sgr A West, the Galactic dynamical nucleus, Sgr A*, thought to be a massive ($M \simeq 2.6 \times 10^6 M_\odot$) black hole (Haller et al. 1996; Genzel et al. 1997; Ghez et al. 1999). Sgr A East has a major axis length of about 10.5 pc and its center is located 2.5 pc from Sgr A* in projection, and probably behind the latter (Goss et al. 1989). Lo et al. (1998) have recently determined the intrinsic size of Sgr A* to be less than 5.4×10^{11} m at λ7mm.

Also located at the GC is the EGRET-identified γ-ray source 2EG J1746-2852 (Mayer-Hasselwander et al. 1998). It has been shown that the high energy $(0.1 - 10 GeV)$ γ-ray emission spectrum of this source is very likely due to the decay of π^0's (Melia et al. 1998; Markoff, Melia & Sarcevic 1997). These pions are produced by p-p collisions which might plausibly take place at either of two shock regions: 1) the shock at Sgr A* due to gas accretion from ambient winds, or 2) the shock produced by the expansion of the SNR-like nonthermal shell of Sgr A East into the ambient gas of the interstellar medium. Thus, *a priori*, either or both Sgr A* and Sgr A East might be the source of the γ-rays which constitute 2EG J1746-285. It has recently been shown, however, that the identification of Sgr A* with 2EG J1746-28 is disfavored because charged leptons produced in $\pi^\pm$ decays would emit too much synchrotron flux in Sgr A*'s intense magnetic field at GHz frequencies to be consistent with the well-studied radio spectrum of this object (Melia et al. 1998; Blasi & Melia 1999).

On the other hand, given the physical conditions in Sgr A East, the putative charged

leptons generated there have a distribution that mimics a power-law with index ~ 3. The synchrotron flux radiated by these charges is consistent with the radio spectrum of Sgr A East observed with the VLA. In fact, such relativistic electrons and positrons would also radiate by bremsstrahlung and undergo inverse Compton scattering in such a way as to self-consistently explain the entire broadband emission spectrum of Sgr A East, ranging from GHz frequencies all the way up to the TeV energies observed by Whipple (Buckley et al 1997). For the purposes of this paper, then, we shall take it that the EGRET source 2EG J1746-285 is identical with Sgr A East (Melia et al. 1998). We note in passing that the maximum energy attained by the shocked protons at Sgr A East, given the energy loss rate via collision in the shock, is $\sim 5 \times 10^{15}\ eV\ =\ 5000\ TeV$ (Melia et al. 1998).

Regardless of the ultimate identity of the EGRET source 2EG J1746-285, given that the process producing the high energy emission is pionic, there should be an associated neutrino flux from the GC (Blasi & Melia 1999). These neutrinos are due both to direct pion decay ($\pi^{\pm} \rightarrow \mu\nu_{\mu}$) and to the decay of muons to electrons and positrons ($\mu^{\pm} \rightarrow e\nu_e\nu_{\mu}$), where we take ν to mean ν and $\overline{\nu}$ here (as we shall often do in the remainder of this paper). *Prima facie*, then, we expect the flavor composition of the neutrino 'beam' generated at the GC to be essentially 67% μ-like and 33% e-like by naïve channel counting (c.f. atmospheric neutrinos in the GeV energy range). Note that there is a ν_{τ} background produced at the source due to non-pionic processes like charmed hadron decay. This background is, however, small; see later. Of course, in the absence of neutrino flavor oscillations, one would expect to observe G.C. neutrinos at Earth with the same flavor composition as that generated at the source.

We do not distinguish between ν and $\overline{\nu}$, because present and planned terrestrial detectors do/will not distinguish between the two. There is one interesting proviso to this statement, however: a $\overline{\nu}_e$ flux at $E_{\overline{\nu}_e} \simeq 6.4 \times 10^3\ TeV\ =\ 6.4 \times 10^{15}\ eV$ can be detected by

resonant W^- boson production via $\overline{\nu}_e e^- \rightarrow W^-$ with the electrons in the detector medium. The resonance energy, however, is just above that attained by neutrinos generated in the processes described above at the GC (Glashow 1960; Berezinsky & Gazizov 1977; Gandhi et al. 1996,1998).

Given our detailed knowledge of the basic physical processes producing the GC γ-rays, we are able to determine an expression for the total neutrino emission at the source, $Q_\nu(E_\nu)$, in terms of the γ-ray emission there, $Q_\gamma(E_\gamma^0)$, the numerical power of the proton spectrum at the source, α (such as would result from shock acceleration at either Sgr A East or Sgr A*), and $r \equiv (m_\mu/m_\pi)^2$ (Blasi & Melia 1999). The quantity α has been empirically-determined to lie between 2.1 and 2.4 (Markoff, Melia & Sarcevic 1997; Blasi & Melia 1999), using a procedure to fit the EGRET spectrum of 2EG J1746-2852 with a detailed calculation of the particle cascade using an extensive compilation of pion-multiplicity cross-sections. In the energy range between the Δ-resonance ($\sqrt{s} \sim 1$ GeV) and the ISR (Intersecting Storage Rings) range ($\sim 23-63$ GeV), simple scaling (Feynman 1969) does not adequately take into account the strong dependence of the cross section on the rapidity at lower energy, and the pion distribution is not adequately described by a power-law mimicking the injected relativistic proton distribution between ~ 1 and ~ 100 GeV. Instead, the distribution steepens in this region and is curved, which is consistent with the suggested spectral shape measured by EGRET. Above about 10 GeV, however, the pion distribution settles into the 'asymptotic' form suggested by scaling, where the power-law index is a direct reflection of the underlying relativistic protons. Thus, an EGRET spectrum with an effective spectral index of ~ -3 below 10 GeV is produced by a pion distribution whose power-law index lies in the range $2.1-2.4$ above this energy. In other words, a relatively steep and curved γ-ray spectrum below 10 GeV is consistent with a flatter neutrino spectrum at TeV-energies. The relative normalization between the γ-ray and neutrino distributions is effected at 10 GeV where the pions take on a power-law form.

We take the neutrino spectrum at Earth to be, in general, given by:

$$\Phi_\nu(E_\nu) = \Phi_\nu(10\ GeV)\ (E_\nu/10\ GeV)^{-\alpha} \tag{1}$$

Normalizing to the observed γ-ray flux at Earth at 10 GeV, one arrives at the following values for the total neutrino flux here (Blasi & Melia 1999):

$$\Phi_\nu(E_\nu) = 1.1 \times 10^{-9}\ (E_\nu/10\ GeV)^{-2.1}\ \ cm^{-2}\, s^{-1}\, GeV^{-1} \tag{2}$$

for $\alpha = 2.1$, and

$$\Phi_\nu(E_\nu) = 9.6 \times 10^{-10}\ (E_\nu/10\ GeV)^{-2.4}\ \ cm^{-2} s^{-1} GeV^{-1} \tag{3}$$

for $\alpha = 2.4$, where we have taken the absolute upper bound to the energy spectrum of G.C. neutrinos to be given by the highest energy ($5 \times 10^{15} eV$) of the shocked protons. (Kinematical calculations show that neutrinos created by the decay of charged pions produced in scattering of a 'beam' proton off a stationary 'target' proton can attain energies very close to the 'beam' proton.) Note that in the above we make the very reasonable assumption that high energy γ's and ν's travel to Earth equally unimpeded by the ambient matter they encounter (which has a column number density of barely $10^{23}\ cm^{-2}$).

Two factors improve the odds for the detection of the GC neutrino flux above the atmospheric neutrino background. These are 1) the effectively point-source nature of the GC, and 2) a GC neutrino spectrum that is significantly flatter than that of atmospheric neutrinos (which goes as $E_\nu^{-3.7}$). If we preliminarily adopt an angular resolution of $\theta_{res} \sim 2^\circ$ for the proposed large scale detectors (1 km^2 effective detector area), the condition for the detection of the GC neutrino flux is $\Phi_\nu(E_\nu)/\Omega_{res} > I_{atm}(E_\nu)$, where $\Omega_{res} \approx \pi\theta_{res}^2$ is the solid angle corresponding to the angular resolution of the experiment and $I_{atm}(E_\nu)$ is the flux of atmospheric neutrinos per unit solid angle. This condition is fulfilled above a few TeV, and the expected event rate from this preliminary analysis is $\sim 4\ km^{-2} yr^{-1}$ for $\alpha = 2.4$

to $\sim 70\ km^{-2}yr^{-1}$ for $\alpha = 2.1$ (Blasi & Melia 1999). Note that a fuller analysis of event rates (presented later) must also consider the problems posed by the atmospheric *muon* background and Earth neutrino opacity.

We see therefore that preliminary calculations reveal that there is a well-determined and potentially observable neutrino flux at the Earth from the Galactic Center. We now briefly list the motivations behind this work before going on to consider whether any sort of neutrino oscillation signature might be detectable in the GC signal.

1.2. Summary of Motivations

The main motivations behind the present work are:

1. Sgr A East is arguably the most thoroughly understood extra-solar astrophysical source of very high energy neutrinos identified to date. It is thus of fundamental importance for the embryonic science of neutrino astronomy.

2. It is important for general scientific reasons to explore the neutrino oscillation phenomenon in a wide variety of regimes. Because of the high energy scales and the very long baselines involved, astrophysical sources such as Sgr A East provide a novel regime not investigated in previous and current solar, atmospheric, reactor and accelerator neutrino detection experiments. Previous works to have considered propagation effect signatures in galactic and extra-galactic high energy neutrino signals include Learned & Pakvasa 1995, Weiler, Simmons, Pakvasa & Learned 1994, Pakvasa 1995, Roy 1996a,b, Píriz, Roy & Wudka 1996, Enqvist, Keränen & Maalampi 1998, Husain 1998, Halzen & Saltzberg 1998, Bento, Keränen & Maalampi 1999, Iyer, Reno, & Sarcevic 1999, Mannheim 1999, Raffelt 1998.

3. Given that solar and atmospheric neutrino observations have essentially established the existence of neutrino oscillations, it is important to incorporate this propagation effect when examining possible sources for study through neutrino astronomy. Neutrino signals from astrophysical sources are an important complement to electromagnetic signals from same, and they will serve to improve our understanding of the dynamics of important astrophysical objects such as supernova remnants, gamma ray bursters and active galactic nucleii.

2. Neutrino oscillations between Sgr A East and Earth

2.1. Distance Considerations

For purposes of calculational expediency we take the neutrino source Sgr A East to have a linear dimension of 10 $pc \simeq 3 \times 10^{17}$ m. This distance is relevant because we need to know how the neutrino oscillation lengths compare with the size of the emitting object to determine whether the neutrino source is flavor coherent. If the former are small compared to the latter, then, because neutrinos are emitted from all points within the source, the oscillations will be averaged out. Alternatively, if the latter are large compared to the former, then no averaging due to the finite size of the source will be needed and the source is essentially flavor coherent for neutrinos of a given energy. Note that two types of averaging generally need to be done: over distance, and over energy. Thus far we have only considered distance averaging due to the finite size of the ν source. One also has to take into account distance (and energy) averaging due to the detector. For Sgr A East the source distance scales involved are at least six orders of magnitude larger than those for the detector (1 A.U. $\simeq 1.5 \times 10^{11}$ m). Detector-based distance averaging, then, will not impact on calculations concerning Sgr A East. We do not address the issue of energy averaging due to the finite energy resolution of the detector in great detail in this paper.

The distance between source and detector is about

$$8\ kpc \simeq 2.5 \times 10^{20}\ m. \tag{4}$$

2.2. Introduction to Neutrino Oscillations

We consider only 2-flavor oscillation modes $\nu_\alpha \leftrightarrow \nu_\beta$ for simplicity and definiteness. Suppose a beam of flavor α is produced at $x = 0$. Then at a point x distant from the source the oscillation probability is

$$P(\alpha \to \beta) = \sin^2 2\theta \sin^2 \left(\pi \frac{x}{L}\right), \tag{5}$$

whereas the "survival probability" is obviously

$$P(\alpha \to \alpha) = 1 - P(\alpha \to \beta). \tag{6}$$

The parameter θ is the 'mixing angle' which determines the amplitude of the oscillations. The value $\theta = \pi/4$, which leads to the largest possible amplitude, is termed 'maximal mixing'. The parameter L is the 'oscillation length' and is given by

$$L = \frac{4\pi E}{\Delta m^2} \tag{7}$$

in natural units $\hbar = c = 1$. Note that the oscillation length increases linearly with energy. This is important because the high energy scale under consideration ($E > TeV$) stretches the oscillation length. The parameter $\Delta m^2 \equiv |m_1^2 - m_2^2|$ is the squared-mass difference between the two mass eigenstate neutrinos.

Totally averaged oscillations see the second $\sin^2$ factor in Equation (5) set equal to 1/2, leading to

$$\langle P(\alpha \to \beta)\rangle = \frac{1}{2} \sin^2 2\theta. \tag{8}$$

This, to reiterate, can be due to either distance or energy spread or both.

Given the poor statistics of the proposed neutrino telescopes, only modes with large mixing angles, θ, can be probed (unless the MSW phenomenon takes place – see later). The atmospheric neutrino anomaly (for ν_μ's) seen by SuperKamiokande and other experiments clearly indicates large angle vacuum oscillations, however (Fukuda et al. 1998a,b,c; Apollonio et al. 1998). Further, the solar neutrino anomaly (for ν_e's) can be solved by large angle oscillations (or by small angle oscillations through the MSW effect) (Smy 1999). In summary, then, the atmospheric anomaly *definitely* requires a large mixing angle solution, while the solar problem *can* be solved by large angle oscillations.

We now briefly review the various possible solutions to the atmospheric and solar neutrino problems, and then apply the various scenarios to the GC neutrino flux.

2.3. Atmospheric Neutrinos

SuperKamiokande detects a 50% deficit of μ-like atmospheric neutrinos coming up through the Earth (Fukuda et al. 1998a,b,c). They see no deficit of either upward- or downward-going e-like neutrinos. The lower energy downward-going μ-like events are deficient, whereas their high-energy counterparts are not. These data can be explained by close-to-maximal $\nu_\mu \to \nu_x$ oscillations with $x \neq e$ and $x = \tau$ or $x = s$ (sterile). These two alternatives both require parameters in the range:

$$\nu_\mu \to \nu_x \quad \text{with } \Delta m^2_{\mu x} = 10^{-3} \to 10^{-2}\ eV^2 \quad \text{and} \quad \sin^2 2\theta_{\mu x} = 1. \tag{9}$$

(To be strict, the Δm^2 ranges are a little different for the two possibilities because of the 'matter effect' in the Earth, but this will be irrelevant for us (Foot, Volkas & Yasuda 1998; Scholberg 1999).) SuperKamiokande currently favors oscillations to ν_τ over oscillations to a

sterile neutrino at the 2σ level (though this is a very preliminary result) (Takita 1999).

2.4. Solar Neutrinos

The solar neutrino problem can be solved by $\nu_e \rightarrow \nu_y$ oscillations, where $y = \mu, \tau, s$ are all allowed, with one important proviso: if the Los Alamos LSND experiment is correct, then $\nu_e \rightarrow \nu_\mu$ oscillations, with parameters that cannot solve the solar neutrino problem, have already been detected (White 1999). So, if the still-controversial LSND result is correct, then $y = \mu$ is ruled out. The MiniBOONE and BOONE experiments at Fermilab should eventually settle this issue (Bazarko 1999).

The precise oscillation parameter space required to account for the solar data depends on which of the solar neutrino experiments are held to be correct. The two parameter ranges defined below, however, are broadly consistent with all solar data;

1. $\nu_e \rightarrow \nu_y$ with a *small* mixing angle (SMA) θ_{ey} is possible through the MSW effect. If this pertains, then the oscillation amplitude will be far too small to affect Sgr A East neutrinos.

2. $\nu_e \rightarrow \nu_y$ with a very large mixing angle (LMA) $\sin^2 2\theta_{ey} \simeq 1$ is an interesting possibility for the range

$$10^{-3} \gtrsim \Delta m^2_{ey}/eV^2 \gtrsim 10^{-10}. \tag{10}$$

The immediate vicinity of $\Delta m^2_{ey} \sim 10^{-10}$ eV^2 defines 'just-so' oscillations where the oscillation length for solar neutrinos is of order 1 A.U. For larger Δm^2_{ey} values completely averaged oscillations, with a flux suppression factor of $0.5 \sin^2 2\theta_{ey}$, result. Maximal mixing explains almost all of the data with averaged oscillations (excepting the Homestake result (Cleveland et al. 1998), and the controversial SuperK spectral anomaly). Values of

$\Delta m^2_{ey} > 10^{-3}\ eV^2$ are ruled out by the non-observation of $\overline{\nu}_e$ disappearance from reactors (CHOOZ, Palo Verde experiments (Bemporad 1999; Boehm 1999)).

2.5. Atmospheric and Solar Neutrino Data Combined

In summary, for GC neutrinos the following are well motivated scenarios that are composed of 2-flavor subsystems:

1. Large angle $\nu_e \rightarrow \nu_s$ + large angle $\nu_\mu \rightarrow \nu_s'$ (scenario 1).[2]
2. Large angle $\nu_e \rightarrow \nu_s$ + large angle $\nu_\mu \rightarrow \nu_\tau$ (scenario 2).
3. Large angle $\nu_e \rightarrow \nu_\tau$ + large angle $\nu_\mu \rightarrow \nu_s$ (scenario 3).
4. Small angle $\nu_e \rightarrow \nu_y$ + large angle $\nu_\mu \rightarrow \nu_s$ (scenario 4).
5. Small angle $\nu_e \rightarrow \nu_y$ + large angle $\nu_\mu \rightarrow \nu_\tau$ (scenario 5).

We are now in a position to perform a number of simple calculations for neutrino oscillations between the GC and the Earth motivated by the above list of 2-flavor possibilities. Note here that bimaximal (Vissani 1997; Barger 1998; Baltz, Goldhaber & Goldhaber 1998; Jezabek & Sumino 1998; Alterelli & Feruglio 1998; Mohapatra & Nussinov 1998) and trimaximal (Nussinov 1976; Giunti, Kim & Kim 1995; Harrison, Perkins & Scott 1994,1996a,b) mixing scenarios, which are intrinsically 3-flavor, will not be considered in this paper.

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[2]This is the situation predicted by the Mirror Matter or Exact Parity Model. See (Foot, Lew & Volkas 1991,1992; Foot 1994; Foot & Volkas 1995).

Using the atmospheric problem parameters, we see that the $\nu_\mu \rightarrow \nu_x$ oscillation length is given by:

$$L_{\mu x} \simeq 2.5 \times 10^8 \frac{E/(1\ TeV)}{\Delta m^2_{\mu x}/(10^{-2}\ eV^2)}\ m. \tag{11}$$

Therefore, the oscillation length is orders of magnitude less than the size of Sgr A East for the entire neutrino spectrum (which only reaches up to $5 \times 10^{15}\ eV = 5 \times 10^3\ TeV$). This means that the oscillations will be distance averaged, and hence at Earth we expect a 50/50 mixture of ν_μ and ν_x, where $x = \tau$ or $x = s$ depending on which solution to the atmospheric problem turns out to be the correct one.

Using the solar problem parameters one determines the $\nu_e \rightarrow \nu_y$ oscillation length to be

$$L_{ey} \simeq 2.5 \times 10^{15} \frac{E/(1\ TeV)}{\Delta m^2_{ey}/(10^{-9}\ eV^2)}\ m. \tag{12}$$

The reference Δm^2_{ey} is in the 'just-so' range. The oscillation length of $\nu_e \rightarrow \nu_y$ oscillations in this range, therefore, becomes larger than Sgr A East for $E > 10 - 100\ TeV$ or so. This means that the more energetic component of the ν_e beam from the source is flavor-coherent.

In principle, such coherence would evidence itself by an energy dependent spectral distortion; the ν_e flux at a particular energy ($E \rightarrow E + \Delta E$) would depend on the part of the neutrino oscillation wave (for that particular energy) encountered by the Earth at its distance from Sgr A East, i.e. the neutrino flux at a particular energy might be anything from maximally suppressed to unsuppressed depending exactly on Δm^2_{ey} and the source-observation point distance. Certainly, ranging over the expected energy spectrum (and therefore ranging over L_{ey}), we should see the flux vary (over and above the variation given by the spectral shape) between maximally suppressed and unsuppressed. Imagining, then, that we had both a neutrino detector able to determine the energy of an incoming neutrino to arbitrary accuracy, and that we had a very long time to accumulate statistics, we should be able to find an experimental signature of the flavor-coherence in the form of this spectral distortion (and thus determine whether Δm^2_{ey} were in the 'just-so' energy range

able to lead to such coherence, and, if it were, exactly what value it takes). Pragmatically, given the small statistics that will accrue from the GC source and the limited energy resolution expected to be achieved by any of the proposed neutrino telescopes, one expects no observational consequence of the flavor coherence. This is because the energy dependence of the flux suppression washes out with the inevitably large size of the energy bins particular neutrino events are accumulated into. The beam, therefore, is indistinguishable from one in the distance-averaged oscillation regime.

Note also that the $\nu_e \rightarrow \nu_y$ oscillation length would become of the order of the GC-Earth distance for $E \sim 10^{16}\ eV$ for $\Delta m^2_{ey} = 10^{-9}\ eV^2$. The ν_e flux would, then, rise from being suppressed below $10^{17}\ eV$ to unsuppressed above $10^{17}\ eV$ if the ν_e attained this energy. Of course given that the maximum energy of the shocked protons does not surpass $\sim 5 \times 10^{15}\ eV$ this phenomenon does not occur for the GC source.

At the opposite extreme of the acceptable parameter space, i.e., $\Delta m^2_{ey} \simeq 10^{-3}\ eV^2$, the oscillation length is

$$L_{ey} \simeq 2.5 \times 10^9 \frac{E/(1\ TeV)}{\Delta m^2_{ey}/(10^{-3}\ eV^2)}\ m. \tag{13}$$

This is back in the totally distance-averaged oscillation regime. In conclusion, for the entire allowable Δm^2_{ey} regime we pragmatically expect a situation similar to the muon-type neutrino case: totally averaged oscillations, i.e., a 50/50 mixture of ν_e and ν_y for maximal mixing.

2.6. Matter Effects?

A brief calculation is sufficient to show that for the GC, matter effects (refractive indices for neutrinos) do not impinge significantly on the oscillation probabilities. The quantities that have to be compared are $\Delta m^2/2E$ and $\sim G_F n$, where G_F is the Fermi constant, and

n is the electron minus positron number density for the medium. Right at the source we expect $n \sim 0$ because of the equal production of electrons and positrons there. Concerning propagation of the neutrinos from source to detector, we have that the interstellar medium consists of approximately 1 H atom per cm^3 so that $G_F n \simeq (10^{-5}\ GeV^{-2})(2 \times 10^{-14}\ GeV)^3$, converting the number density to natural units. This number works out to be about $10^{-46}\ GeV$. The smallest Δm^2 we consider is $10^{-10}\ eV^2 = 10^{-28}\ GeV^2$ and for the highest attainable neutrino energy of $5 \times 10^{15}\ eV = 5 \times 10^6\ GeV$, we get $\Delta m^2/E \sim 2 \times 10^{-35}\ GeV$, so we are 11 orders of magnitude away from having important matter effects due to the interstellar medium. We do not consider matter effects due to dense intervening objects between the GC and Earth, since their covering fraction for Sgr A East is trivially negligible.

2.7. Observational Consequences – in Theory

We consider now the observational consequences of scenarios 1 to 5 listed above in terms of the neutrino flux at Earth (we remind the reader that all ν_μ mixing scenarios are LMA).

1. Scenario 1 (LMA $\nu_e \to \nu_s$ and $\nu_\mu \to \nu_s'$): 50% reduction of both ν_e and ν_μ flux, and no ν_τ appearance above background.

2. Scenario 2 (LMA $\nu_e \to \nu_s$ and $\nu_\mu \to \nu_\tau$): 50% reduction of ν_e flux, and equal ν_μ and ν_τ fluxes.

3. Scenario 3 (LMA $\nu_e \to \nu_\tau$ and $\nu_\mu \to \nu_s$): Equal ν_e and ν_τ fluxes, and 50% reduction of ν_μ flux.

4. Scenario 4 (SMA $\nu_e \to \nu_y$ and $\nu_\mu \to \nu_s$): Unreduced ν_e flux, 50% reduced ν_μ flux, no ν_τ appearance above background.

5. Scenario 5 (SMA $\nu_e \to \nu_y$ and $\nu_\mu \to \nu_\tau$): Unreduced ν_e flux, and equal ν_μ and ν_τ fluxes.

The scenarios above imply the following ratios (and ratios of ratios) of neutrino flavor fluxes:

Ratio	No Oscillations	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
$(\Phi^{obs}_{\nu_e}/\Phi^{theor}_{\nu_e})$	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
$(\Phi^{obs}_{\nu_\mu}/\Phi^{theor}_{\nu_\mu})$	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
$(\Phi^{obs}_{\nu_e}/\Phi^{obs}_{\nu_\mu})$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
$(\Phi^{obs}_{\nu_\tau}/\Phi^{obs}_{\nu_\mu})$	$\ll 1$	$\ll 1$	1	$\frac{1}{2}$	$\ll 1$	1
$\frac{(\Phi_{\nu_e}/\Phi_{\nu_\mu})^{obs}}{(\Phi_{\nu_e}/\Phi_{\nu_\mu})^{theor}}$	1	1	1	1	2	2
$\frac{(\Phi_{\nu_\tau}/\Phi_{\nu_\mu})^{obs}}{(\Phi_{\nu_\tau}/\Phi_{\nu_\mu})^{theor}}$	1	2	$\gg 1$	$\gg 1$	2	$\gg 1$
$\frac{(\Phi_{\nu_e}/\Phi_{\nu_\tau})^{obs}}{(\Phi_{\nu_e}/\Phi_{\nu_\tau})^{theor}}$	1	$\frac{1}{2}$	$\ll 1$	$\ll 1$	1	$\ll 1$

The superscript '*obs*' denotes the flux ratios observed by a neutrino telescope, while '*theor*' denotes the ratio expected from the no-oscillation theoretical calculation. Deviation away from the value predicted for the no oscillation case in any of the ratios defined above, beyond experimental uncertainty, would constitute a *prima facie* case for whatever neutrino oscillation scenario most closely predicts the experimental fluxes. Deviation in the third last ratio would constitute the strongest evidence for oscillation because errors due to uncertainties in the determination of the total theoretical neutrino flux tend to cancel in taking the ratio of the theoretical ν_e and ν_μ flavor ratios given that ν_e's and ν_μ's are produced by the same mechanism at the source.

On the other hand, there is considerable uncertainty concerning the ν_τ background (see later) so that estimates of $\Phi^{theor}_{\nu_\tau}$ may not be particularly meaningful. For this reason,

we do not list $(\Phi_{\nu_\tau}^{obs}/\Phi_{\nu_\tau}^{theor})$. As displayed above, though, in the absence of oscillations we still expect the ν_τ flux to be considerably smaller than the other flavor fluxes in the absence of oscillations to this flavor type. Further, deviation from 1 in the first two ratios defined could only provide strong evidence of oscillations if the uncertainties in the power of the neutrino spectrum, α, and $\Phi_\nu(10\ GeV)$ were both significantly reduced by future γ-ray observations using instruments with better energy resolution and coverage. The GLAST mission may be the first to provide the necessary improvements over the next few years (Gehrels & Michelson 1999).

Note also that, unfortunately, none of the five scenarios considered here realistically exhibits the energy-dependent flux suppression (within an appropriate energy range) that would be the most telling signature of neutrino oscillations. Further, even assuming that we possess a detector with near perfect neutrino identification capability, so that we can determine the ratios defined above and hence distinguish between the five broad scenarios, we still cannot further pin down $\Delta m_{\mu x}^2$ or Δm_{ey}^2 than has already been achieved with the terrestrial solar, atmospheric, reactor and accelerator neutrino experiments.[3] The allowable mixing angle parameter space might only be constrained in the sense that the above ratios distinguish between a large and a small θ_{ey}.

In the next section we examine the prospects for determining the neutrino flux of each flavor at Earth.

3. Detection of Oscillations

[3]As noted previously, however, with perfect energy resolution the potential flavor coherence of Sgr A East over at least some of the $\Delta m_{ey}{}^2$ parameter space *would* have an experimental signature.

3.1. The Detectors

In this work we consider only the Čerenkov neutrino telescopes now in planning and construction stages as observation platforms. Other proposed astronomical neutrino detection methods tend to require neutrino energies in excess of that possessed by Sgr A East neutrinos (see appendix C of (Rachen & Mézáros 1999) for a brief review).[4]

The Čerenkov detectors are planned to operate through the instrumentation of very large volumes ($\sim 1km^3$ is thought to be optimal for astronomical neutrino detection (Halzen 1998)) of some transparent medium (in practice water or ice) with photomultiplier tubes (PMTs). These tubes will detect the Čerenkov light generated by superluminal charged leptons traversing the detector volume. The Čerenkov light is generated at a characteristic angle (for the medium) away from the direction of travel of the charged particle. Note that only muons and extremely energetic tauons have path lengths through water and ice significant on the scales of the PMT separation of these detectors (tens of meters). Electrons are arrested very quickly (within a meter or so), even at the highest energies we are considering: $O[PeV]$. Lower energy tauons (produced by ν_τ primaries with $E_{\nu_\tau} < 10^{14}\ eV$) decay within meters.

We remark in passing that, at considerably higher energies still (i.e., $\sim 20\ PeV$),

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[4]The two most interesting alternative neutrino detection techniques are the use of air shower arrays and radio detection of neutrino interactions in ice. Air shower arrays, which probably offer the best hope for ν_e detection and identification, are limited to energies in excess of $\sim 10^{17}\ eV$ by the atmospheric background (Capelle et al. 1998). Radio detection of neutrinos will probably require energies at or in excess of the GC neutrino energy upper limit (i.e., $5 \times 10^{15}\ eV$) because of signal-to-noise problems (Gaisser, Halzen & Stanev 1995; Alzarez-Muñiz, Vázquez and Zas 1999; Alzarez-Muñiz & Zas 1999).

the Landau-Pomeranchuk-Migdal (LPM) effect starts to cause a measurable reduction to the pair production and bremsstrahlung cross sections of the electron. This increases the radiation lengths of $e^{\pm}$ (Alzarez-Muñiz & Zas 1997).

Čerenkov neutrino telescopes of course encounter background generated by atmospheric *muons* (i.e., muons generated directly by cosmic ray interactions in the atmosphere) as well as the atmospheric *neutrino* background. In fact, this background overwhelms the genuine neutrino signal due to any conceivable astronomical object at sea level and hence neutrino telescopes must be shielded somehow. This requirement (as well as the requirement for sufficient clarity of the medium) is what has driven all proposed sites for working neutrino telescopes deep (few kilometers) into the Antarctic icecap or underwater.

Even at these depths, however, the atmospheric muon background is far from negligible. The simplest way to ensure exclusive selection of genuine neutrino-generated leptons against this background is to have a Čerenkov detector register only 'upcoming' leptons; those that arrive at a specified angle to the vertical somewhat below the horizontal. It is then almost assured that such charged leptons have been generated by neutrinos which traverse some large fraction of the Earth's diameter and then subsequently undergo charged current (CC) interactions with the water/ice at the detector or the rock/water/ice fairly close to it. Exclusive selection for upcoming leptons can be achieved through a combination of geometry (simply situating all PMTs so they face downwards) and triggering (which can discern up-going from down-going signal on the basis of fairly simple timing considerations (Spiering 1999; The AMANDA Collaboration 1999)). Note that the highest energy muons might traverse a distance of ten kilometers water equivalent and still retain sufficient energy to produce a detectable Čerenkov signal (Gandhi et al. 1996,1998). The effective volume, therefore, for ν_μ detection is substantially larger than the 'instrumented' volume.

Of course, such a simple triggering system (and geometry) means that one misses

out completely on the signal from down-going neutrinos (which also generate down-going leptons in CC interactions). This may seem like a reasonable compromise (the effective detector area is greater from below, after all, because of the greater amount of material below the detector than above) until one considers the fact that for high energy neutrinos Earth 'shadowing' or opacity becomes a significant effect. A neutrino is shadowed when its interaction length becomes smaller than the distance it must travel through the Earth to reach a detector. At energies of $\sim 10^{15}\ eV$ Earth opacity affects all neutrinos except those that reach a detector from an almost horizontal direction. It would seem, therefore, that with the scheme described above – reject all down-going leptons – and the unavoidable issue of Earth opacity, ultra high energy neutrino telescopy is impossible, except for a tiny window on neutrinos which come from a practically horizontal direction.

In order for ultra high energy neutrino astronomy to have a future, detector triggering must be designed that does something smarter than simply rejecting all down-going leptons; it must be able to select something of the genuine down-going signal, at least at higher energies. For the moment, let us assume that some more discerning trigger can be instantiated. The question now is, does the GC neutrino source have a large enough flux at high energies to be seen against the muon background (for reasonable values of telescope angular resolution), even in principle?

To make this calculation, we first adopt values for the high energy (vertical) fluxes of atmospheric muons at sea level given elsewhere (Thunman, Ingelman & Gondolo 1996, fig.3) and then convolve these fluxes with values for the probabilities of these muons to reach the particular water and ice depths of the proposed detectors (Antonioli et al. 1997) Then, to determine event rates in a detector due to high energy atmospheric muon background, we take these fluxes over a sensible range of telescope angular resolutions (from 2.0° to 0.3°, say). Subsequently, we compare these (angular resolution dependent) rates with the

genuine, neutrino-generated event rate found by convolving the GC neutrino spectrum with reasonable estimates for the neutrino detection probability.

The probability that a high energy muon-type neutrino is detected in a km^3-scale neutrino telescope depends on two factors, viz; approximately inversely on the interaction length of the neutrino (λ_{int}) at that energy (which, in turn, depends on the charged current cross-section) and approximately directly on the radiation length of the muon (R_μ) produced in the interaction. (We assume here that the linear dimension of the detector is small on the scale of R_μ.) We can make a rough estimate of the effect of these factors by writing down a detection probability multiplier which goes as some power of the energy:

$$P_{\nu\to\mu} \simeq \frac{R_\mu}{\lambda_{int}} \simeq A{E_\nu}^n.$$

Halzen gives $n = 0.8$ and $A = 10^{-6}$ for TeV to PeV energies, with E measured in TeV units (Halzen 1998).

Note here paranthetically that all proposed neutrino detectors will have an overburden depth less than the radiation length of muons with energies in the energy range we are considering (see later). This means that the above method actually over-estimates the neutrino detection probability for downward-going neutrinos because the volume of material *above* a detector available for the neutrino to interact within (and subsequently produce a muon which might then travel on to the detector volume) is substantially less than that for upward going neutrinos.

Employing the above (generous) parameterization of the neutrino detection probability allows us to determine that the GC signal does not, in fact, emerge clearly from the background until well into the upper end of the neutrino energy spectrum (even for a detector resolution as low as 0.3° and the flattest empirically allowable neutrino spectrum, $\alpha = 2.1$). It seems that even granted a detector able to trigger on neutrino-generated, down-going leptons, we cannot, on the basis of our preliminary calculations, confidently

conclude that we might see the GC source in such a way. We therefore restrict ourselves to consideration of the Sgr A East signal to be found in upcoming leptons.

An immediate consequence of this self-imposed restriction is that we are unable to reach many conclusions about the usefulness of the (successor to the) AMANDA neutrino telescope in regards to observing the GC. This is somewhat unfortunate because the AMANDA experiment, of all neutrino telescope projects, is probably the best currently placed to realize the desired km^3 status and thus evolve to 'IceCube' (The IceCube Collaboration). [5] This is because AMANDA/IceCube's South Polar location means that the GC is always overhead fom the detector. A detector specific Monte Carlo calculation will probably be needed to settle whether our particular source can be seen by IceCube. We can predict, however, that IceCube may well be able to detect the distinctive 'double bang' signature of GC ν_τ interactions above the background; see later.

We must, therefore, look to the Northern Hemisphere for ν_μ observing platforms about which we can make more confident predictions regarding the GC source. There are currently four neutrino telescope projects under development there. The Lake Baikal project is a mature experiment, having run on and off since 1993. This collaboration has achieved an effective, energy-dependent detector area of $1000 - 5000\ m^2$ and has demonstrated the viability of large-scale, water-based Čerenkov technology. The collaboration is planning for a neutrino telescope of $5 - 10 \times 10^4\ m^2$ effective area. This will not be a large enough platform for the relatively high energy (and low flux) neutrino signal generated at Sgr A East (Balkanov et al. 1999).

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[5]The IceCube project, given that it continues to pass through scientific review and find funding, will go into construction in the 2001-2002 Antarctic season and should take 6-7 years to complete. The detector will be operated as it grows (Halzen 2000).

Three other projects, all based in the deep Mediterranean, are currently in the design and prototype stage. They are ANTARES, NESTOR and NEMO. None of these projects is guaranteed of the funds to reach km^3 status, though this is the stated goal of all three collaborations. Needless to say, these deep sea environment projects call for great ingenuity and considerable technical innovation.

The ANTARES collaboration has completed preliminary reconnaissance of its chosen site at a depth of 2400m below the sea near Toulon. They are also well into design of electronics and mechanics for the detector. The collaboration's current mid-term goal is to have 13 'strings', with $\sim$ 1000 attached PMTs, in place by 2003. Such a configuration would have an effective area of 0.1 km^3 (The ANATRES Collaboration 1999).

The NESTOR collaboration plans for a deployment at $\sim$ 4000 m depth off the south west Grecian coast. This collaboration is at a similar stage of advancement to the ANTARES group, having completed reconnaissance of their chosen site and preliminary field testing of crucial components. NESTOR also aims for a 0.1 km^2 effective area detector in the near future (Trasatti 1999).

Lastly, the NEMO project is least advanced being in the early R&D stage. This collaboration is investigating the suitability of a site off the southern Italian coast. They have conducted Monte Carlo studies of their proposed detector layout (Montaruli 1999).

In conclusion, one does not expect to see a km^3 neutrino telescope in the Northern Hemisphere within a decade, but within two decades the chances for such would seem to be quite good.

3.2. Neutral Current Interactions

Neutral current (NC) interactions do not identify the incoming neutrino flavor and basically constitute a background to the more useful charged current interactions. Energy determination for NC events is poor because of the missing final state neutrino. Angular determination is also poor because the single hadronic shower produced is almost point-like on the scale of a typical detector's PMT spacing. NC interactions are only about one third as common as CC interactions.

3.3. Muon Neutrinos

The best prospects for observing *any* neutrino flux from the GC source are offered by muon type neutrinos; ν_μ's and $\overline{\nu}_\mu$'s (we remind the reader that neutrino telescopes cannot distinguish a neutrino from an anti-neutrino of the same flavor type). Charged current interactions of a muon type neutrino in or near the detector volume result in a nearly point-like hadronic shower and a high energy muon ($\mu^\pm$) which, we reiterate, might travel up to ten kilometers and still possess enough energy to be detected. Certainly in the above-100 GeV energy scales of relevance to this paper, muons will be 'uncontained' in the sense that they cannot be expected to be both generated and arrested within the km^3 detector volumes. Such long tracks mean, of course, very good determination of the muon's direction of travel. On the other hand, the fact that the muons are necessarily uncontained leads to uncertainty in energy determination. We now discuss, in the context of the observation of neutrino-generated muons, the general issues of angular and energy determination in more detail.

3.3.1. Energy Determination

An accurate determination of the energy possessed by a muon neutrino (which produces a muon observed by a detector) is limited by three factors: uncertainty in the fraction of the neutrino's total energy imparted to the muon, ignorance of the energy loss by the muon outside the instrumented volume and, finally, the intrinsic energy resolution of the detector apparatus itself (The ANATRES Collaboration 1999).

Regarding the first factor, it can be shown that the average energy imparted to the muon is half that of the neutrino in the CC interaction $\nu_\mu d \rightarrow \mu^- u$ and three quarters in the interaction $\overline{\nu}_\mu u \rightarrow \mu^+ d$ (The ANATRES Collaboration 1999). A determination of an individual muon's energy, then, might only give us a minimum energy for the neutrino primary but this problem is not a limiting factor if a significant number of events can be accumulated and we take a statistical view.

Note that when the muon is uncontained and, hence, an accurate determination cannot be achieved by measuring the length of the entire muon track, a rougher muon energy determination can be achieved for $E_\mu > 1\ TeV$ by measuring dE_μ/dx because at such energies, where energy loss is dominated by radiative processes, $(dE_\mu/dx) \propto E$. It may also eventually be possible to glean some neutrino energy information from the hadronic shower resulting from the first CC interaction if this happens to be within the detector volume (keeping in mind the difficulty posed by the relatively small size of such showers on the scale of a next-generation detector's PMT spacing).

That we are dealing with uncontained muon tracks means that one can only arrive at a minimum original muon energy. That we can make some sort of energy determination from dE_μ/dx, though, means that we have a much better idea of the original energy of a *totally* uncontained muon than would be imparted by just assigning it a minimum energy enough to take it across the detector.

Given all the above factors, the ANTARES collaboration has judged on the basis of Monte Carlo simulations of their detector array that they can gauge a muon neutrino's energy to within a factor of three for $E_\nu > 1\ TeV$ (The ANATRES Collaboration 1999).

3.3.2. Angular Determination

Again three factors limit the determination of the primary neutrino's direction of travel. These are the uncertainty in the angle between the incoming ν_μ and the resulting μ, the deviation of the μ away from its original direction of travel due to multiple scattering and, lastly, the detector's intrinsic angular resolution as determined by uncertainties in its exact geometry, etc. (The ANATRES Collaboration 1999). Of course, the severity of the first two problems decreases with increasing energy, but the relative severity of the two likely changes with energy. For example, the ANTARES collaboration has determined from MC simulations that below 10 TeV total angular resolution is limited by detector effects whereas above 100 TeV it is limited by the unavoidable angular distribution of the neutrino interactions. They claim an angular resolution of 0.3° is achievable (The ANATRES Collaboration 1999). With such a resolution the GC signal is above atmospheric neutrino background for energies greater than a few $\times$ 100 GeV.

The AMANDA project (which will hopefully evolve into IceCube) has to contend with the short scattering length of the Čerenkov light in ice, $> 200m$, as compared to seawater at $24m$. Despite this, IceCube will achieve an angular resolution less than one degree and perhaps as low as 0.4° (Halzen 2000). We note parenthetically that such a resolution will mean that many southern sky sources (i.e. sources of downgoing neutrinos) *will* be able to be seen by IceCube above atmospheric muon background.

3.3.3. Earth Opacity

At $\sim 4 \times 10^{13}$ $eV = 40$ TeV the interaction lengths of all neutrino flavors become less than the Earth's diameter. This means that, in particular, ν_μ's are unlikely to reach a detector from a nadir angle of $0°$ (The ANATRES Collaboration 1999). (The same is true for ν_e's but *not* ν_τ's; see later.) The attenuation of the ν_μ interaction length continues until at $\sim 10^{15}$ eV it is less than a very small fraction of the Earth's diameter, so that this flavor is attenuated over all nadir angles, even those approaching the horizontal. At such high energies, then, the Earth is said to be 'opaque' to ν_μ's (and ν_e's) (Nicolaidis & A. Taramopoulos 1996). We must take both this effect and our self-imposed requirement that the GC neutrino source be below the horizon from the observation point (in order to avoid the atmospheric muon background problem) into account to generate a more realistic estimate of the event rate due to the GC source.

Let us assume the best case scenario for ν_μ fluxes – detector angular resolution of $0.3°$, and a neutrino spectrum that goes as $\alpha = 2.1$ – to make a determination of the expected event rate in a hypothetical, km^3 detector located on the proposed ANTARES site. Note that with this revised angular resolution, the GC neutrino flux is above atmospheric neutrino background at an energy around an order of magnitude lower than previously: a few 100 GeV. Also note that the GC is below the horizon about two thirds of the time from this latitude (Zombeck 1990) and, therefore, invisible at least one third of the time (even if low enough detector resolution were achieved to unequivically avoid the atmospheric muon background problem, ANTARES is being designed with downward pointing PMTs). Adopting the neutrino penetration coefficients calculated by Naumov and Perrone (Naumov & Perrone 1999, fig.3), we determine that the expected annual event rate from ν_μ's generated at the GC is ~ 40 for the no-oscillation case and ~ 20 if oscillations do occur. For $\alpha = 2.4$, but retaining an angular resolution of $0.3°$, we expect ~ 5 events without

oscillation and ~ 2 with. Clearly, then, we approach the lower end of statistical relevance with this value for α. (In these calculations we have not allowed for the regeneration effect due to NC interactions that affects all neutrino flavors. We expect this effect to be small (Kwiecinski, Martin, & Stasto 1999).)

3.3.4. Muon Neutrino Background

We note, in passing, one unavoidable source of ν_μ background; CC ν_τ interactions can mimic CC ν_μ interactions if 1) the ν_τ energy is too low to effectively separate the original CC interaction vertex and the τ decay vertex, and 2) the τ decays muonically (the branching ratio for this decay is ~ 17 % (Caso et al. 1999)).

3.4. Electron Neutrinos

In contrast to the case for muon neutrinos, the prospects for identifying electrons ($e^{\pm}$) in a detector generated by ν_e's from the direction of the GC seem remote. Quite a few of the significant problems with observing the ν_e signal can be related back to the relatively tiny propagation length ($\sim$ meter) of high energy electrons (and positrons) in matter. Perhaps most significant is that, as with NC interactions, the hadronic and electromagnetic showers initiated by a ν_e in a CC interaction have almost point-like dimension on the scale of the proposed detectors and, hence, provide little directional information. Thus, even if we grant that an electron signal in the appropriate energy range for the GC source might be identified, we cannot actually identify the origin of the primary electron neutrino.

A second problem is that electron neutrino initiated CC events are very difficult to conclusively identify. In principle a smoking gun for such events is presented by the coincident presence of both a hadronic shower (from the disturbed nucleus) *and* an

electromagnetic shower from the quickly braked $e^{\pm}$. It is very difficult, however, for the proposed, next-generation Čerenkov technology to distinguish between the two types of showers. Both showers, we repeat, are essentially point-like on the scale of the typical detector's PMT spacing and, after all, are observed only indirectly through the Čerenkov flash they produce. Thus, NC events, which produce a point-like hadronic shower, are difficult to distinguish from CC ν_e initiated events and provide a significant background problem. Further, even imagining that we had some reliable technology to identify the presence of a high energy electron, the CC interactions of ν_τ's can still mimic CC ν_e events if 1) the τ energy is not high enough to ensure that the hadronic shower from the CC interaction of the primary ν_τ and the later decay are effectively separated on the scale of the detector, and 2) the τ decays electronically (with a branching ratio of ~ 18 % (Caso et al. 1999)).

A yet further problem is the fact that the short path of the electron in matter means that one can only register contained ν_e CC events, dramatically reducing the effective volume monitored by the detector in comparison with ν_μ events.

Altogether one cannot but conclude that the chances for detecting GC ν_e's, at this stage, seem remote.

3.5. Tauon Neutrinos

Although the chances for observing GC ν_τ's seem more hopeful than those for GC ν_e's, there will still be considerable problems with this flavor. At least two unique signatures for the ν_τ have been identified in the literature: 1) the 'double bang' and 2) flat angular dependence of the signal or 'pile up' (Nicolaidis & A. Taramopoulos 1996; Learned & Pakvasa 1995; Halzen & Saltzberg 1998; Iyer, Reno, & Sarcevic 1999). These both, however,

tend to become significant on the higher energy side of the GC neutrino spectrum.

3.5.1. Double Bang

In more detail, the 'double bang' signal requires that a ν_τ undergo a CC interaction in the detector volume to produce a τ. If the energy of this τ is high enough then the hadronic shower resulting from the initial interaction of the neutrino primary and the later hadronic shower resulting from the τ decay will be resolvable on the scale of the detector. Exactly where the resolvability threshold is can probably only be determined by detector-specific MC simulations. The ANTARES group believes the signal certainly *cannot* be resolved for $E_{\nu_\tau} < 100\ TeV$ (The ANATRES Collaboration 1999). At $E_\tau \sim PeV$, towards the upper limit of the GC neutrino spectrum, the two bangs should be separated by about $100m$ and clearly resolvable.

The usefulness of this signature, then, will depend on detector specifics and the question of whether a statistically significant flux can be obtained from whatever part of the ν_τ spectrum remains able to produce a signal.

One also notes that Earth opacity will significantly reduce the flux of ν_τ's sufficiently energetic to produce the double bang signal if one is looking for the signal in upcoming neutrinos. It is in searching for the double bang signature from GC ν_τ's, then, that we can predict that AMANDA (or, more precisely, IceCube the km^3 extension of AMANDA) may well find employment in regards to this source; GC neutrinos will not be affected by Earth opacity when observed by IceCube. (The genuine GC ν_τ flux is substantially above that of the atmospheric ν_τ's due to 'prompt' and conventional flux over an angular resolution even as bad as $2°$ (Pasquali & Reno 1999) and $2°$ is a pessimistic prediction for the IceCube's angular resolution (Halzen 2000, Halzen 1998)). Assuming a best-case scenario for ν_τ

detection, viz, the flattest allowable GC spectrum ($\alpha = 2.1$), double bang resolvability all the way down to 100 TeV and $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assuming a double bang detection probability given by 1 $kmwe/\lambda_{int}$ (1 $kmwe$ means 1 km water equivalent), we can arrive at an (optimistic) annual event rate prediction for IceCube.

We derive the double bang detection probability by employing similar logic to that which led to the ν_μ detection probability presented previously. The difference here is that we assume the τ decay length is small on the scale of the linear dimension of the detector (hence the 1 in the numerator), whereas previously we assumed that the μ radiation length is large in comparison to this scale. We employ a parameterization of the neutrino interaction length presented in graphic form (fig. 11) in (Gandhi et al. 1996,1998).

Using the detection probability described above, and the best case scenarios for the GC spectrum and double bang resolvability, we determine an event rate of 1 double bang signal per year. This is at the threshold of detectability.

3.5.2. Pile Up

The idea behind the second ν_τ signature – the flat angular dependence which has recently received attention from Halzen and Saltzberg (1998) and Iyer, Reno, and Sarcevic (1999) – is to actually make positive use of the Earth opacity previously mentioned. When E_{ν_τ} climbs beyond $\sim 4 \times 10^{13}$ eV the interaction length of the ν_τ becomes, as for the ν_e and ν_μ, less than the Earth radius. But whereas e's and μ's resulting from CC interactions are stopped in the Earth, τ's from CC interactions decay back to ν_τ's before being stopped, producing a neutrino with something around one quarter the energy of the original and traveling in much the same direction. This process can occur more than once, each iteration producing a progressively lower energy ν_τ, ensuring that whatever the energy of the primary

ν_τ, a ν_τ signal from a point source should reach a detector on the other side of the Earth. This signal will exhibit a 'pile up' just below the energy where the ν_τ's interaction length becomes greater than the fraction of the Earth's diameter subtended by a ray from the source to the detector.

In other words, for $\nu_{e,\mu}$ energies in excess of $\sim 10^{12}\ eV$, as the angle between a neutrino source and the nadir is decreased from 90°, a critical angle will be reached where the $\nu_{e,\mu}$ flux will begin to be attenuated. This attenuation increases to reach a maximum at 0°. Further, as the energy of the $\nu_{e,\mu}$ signal increases, the flux attenuation sets in at increasingly large (i.e., increasingly horizontal) angles.

On the other hand, the ν_τ flux, although shifted downward in energy, should still be the same. This results in the flat angular dependence of the ν_τ part of the signal at high energies and, given a significant ν_τ component of the total neutrino flux, a flatter than expected angular dependence of the total neutrino flux.

One way to search for a ν_τ signal, then, is through the decay chain $\tau \rightarrow \nu_\tau \mu \nu_\mu$ (branching ratio $\sim 17\%$ (Caso et al. 1999)). Given the above considerations, if we assume that a significant part of a neutrino signal is due to ν_τ's, we expect an enhancement of the number of μ's coming from the direction of our source, below certain energies and nadir angles, over that expected from the 'raw' ν_μ and ν_τ fluxes. In order to see this enhancement, however, we require that the ν energy spectrum not be too steep. Otherwise the increase of the μ flux in some particular, lower energy 'bin' will be insignificant on the scale of the number of events that would be recorded there anyway due to the raw ν_μ and ν_τ fluxes.

Iyer, Reno, and Sarcevic (199) have made calculations of the 'pile up' enhancement for neutrino spectra which go as different negative powers: $n = 1, 2, 3.6$. For $n = 1$ the enhancement is a noticeable effect, but for $n = 2$ and greater the spectra are too steep for the effect to be discernible. For the Sgr A East neutrino flux, with a best-case spectrum

which has an n of 2.1, we must unfortunately conclude that the above diagnostic for the presence of a significant ν_τ component in the total neutrino signal will not be useful.

In summary for the ν_τ case, we believe that the GC can produce ν_τ's energetic enough to produce a double bang signal, but that the spectrum is too steep to evidence ν_τ's with pile up. A preliminary calculation reveals a double bang signal at the threshold of detectability in IceCube, but a confident indication that this signal will produce a statistically significant event rate requires a detector-specific study.

3.5.3. Tauon Neutrino Background

As has been mentioned, we expect no ν_τ flux from pion decay from p-p scattering at the GC in the absence of oscillations and, hence, observation of a ν_τ flux of the order of the ν_e or ν_μ flux constitutes *prima facie* evidence for exactly such neutrino oscillations. One must be concerned, however, about sources of background to the ν_τ oscillation signal, both genuine ν_τ flux from sources that have not been accounted for and false ν_τ signals in the detector.

One source of ν_τ's that we can anticipate at higher energies at the production site is the decay of charmed mesons (principally D_s) produced in p-p scattering through τ and ν_τ production. It should be noted that the cross-sections for c and $\overline{c}$ production via p-p scattering are greatly uncertain in the energy range of interest, as are the fractional likelihood of $c \to D_s$ and the branching ratio for $D_s \to \tau\nu_\tau$ (Caso et al. 1999; Pasquali & Reno 1999). In comparison, however, with pion production processes leading to $\nu_{e,\mu}$ such charmed meson production is still greatly suppressed. The flux ratio ${\Phi_{\nu_\tau}}^{obs}/{\Phi_{\nu_\mu}}^{obs}$ can still, therefore, be expected to be a small number taking this process into account, although there might be considerable deviation from 1 in ${\Phi_{\nu_\tau}}^{obs}/{\Phi_{\nu_\tau}}^{theor}$ (if we assume large statistics)

without oscillations necessarily being implied.

4. Observational Consequences – in Practice

If we grant that the GC source will not produce ν_e's in an observational energy range, might produce ν_τ's in an observational range and certainly will produce observational ν_μ's, we are left with only one useful flux ratio that is certainly measurable:

$$\frac{\Phi_{\nu_\mu}^{obs}}{\Phi_{\nu_\mu}^{theor}}, \tag{14}$$

and two that may be measurable:

$$\frac{\Phi_{\nu_\tau}^{obs}}{\Phi_{\nu_\mu}^{obs}}, \qquad \frac{(\Phi_{\nu_\tau}/\Phi_{\nu_\mu})^{obs}}{(\Phi_{\nu_\tau}/\Phi_{\nu_\mu})^{theor}}. \tag{15}$$

As previously discussed, deviation from one in the first ratio, by itself, would provide only weak evidence for oscillations unless the empirical values of α and $\Phi_\nu(10\ GeV)$ were further constrained (by future γ-ray observations). Even if this were achieved, however, given the indirectness of the $\Phi_{\nu_\mu}^{theor}$ measurement, there would have to be some doubt about whether the presence of oscillations had been conclusively demonstrated. With empirical determination of the values of all three ratios, only scenario 3 emerges with a unique signature. Otherwise, we can only distinguish the $\nu_\mu \to \nu_s$ scenarios (1 and 4) from the $\nu_\mu \to \nu_\tau$ scenarios (2 and 5), without being able to conclude anything about ν_e mixing. Certainly, however, $\Phi_{\nu_\tau}^{obs}/\Phi_{\nu_\mu}^{obs}$ potentially offers very strong evidence of oscillations if it is found to deviate substantially from zero.

Given that the measurement of these ratios lies at least a decade into the future it is, in fact, not unlikely that the uncertainty regarding the ν_e and ν_μ oscillation modes be largely dispelled by the time of such measurement, i.e., other experiments will determine which of scenarios 1 to 5 (or bimaximal or trimaximal oscillations or even one of the non-oscillation

scenarios – see below) actually occurs in nature. The most interesting science that might be extracted from GC neutrino observations, then, may be an empirical determination of α and $\Phi_\nu(10\ GeV)$ independent of γ-ray observations.[6]

Note in passing that determination of the flavor composition of the GC neutrino signal could certainly provide for stringent tests of various alternative, no-oscillation explanations to the solar and atmospheric neutrino anomalies if these are not ruled out in the near future. For instance, a large ν_μ component in the GC neutrino spectrum would imply a much larger lower limit on the 'ν_μ lifetime' (we should, strictly, consider the lifetimes of the mass eigenstates composing the ν_μ) than is required to explain the atmospheric neutrino anomaly. See, e.g., (Barger et al. 1999). On the other hand, flavor changing neutral currents (FCNC), invoked as explanations of the atmospheric anomaly (Wolfenstein 1978,1979; Brooijmans 1998; Gonzalez-Garcia et al. 1998; Lipari & M. Lusignoli 1999), cannot affect the Sgr A East signal. This is because the column density encountered by neutrinos propagating from the GC to the Earth is far too small to allow this mechanism to occur. FCNC explanations of the atmospheric anomaly, then, predict a GC neutrino event rate undiminished from the naïve expectation and deviation from this would tell against such explanations.

5. General Background Problems

There are a number of sources of background to the GC neutrino signal. Logically, we can break these down into the two general classes: 1) 'enshrouded sources' and 2) terrestrial

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[6]With the certain knowledge that $\nu_\mu \rightarrow \nu_x$ oscillations *do* take place and, hence, the knowledge that $\Phi^{obs}_{\nu_\mu}/\Phi^{theor}_{\nu_\mu}$ must be 1/2, and from an empirical determination of the ν_μ spectrum, one can work backwards to obtain $\Phi^{theor}_{\nu_\mu}$ and, thence, α and $\Phi_\nu(10\ GeV)$.

background. By the former we refer to any sources of genuine neutrino signal from the GC which are 'hidden' in the sense that they are not correlated with the GC γ-ray spectrum. By the latter we mean the atmospheric neutrino and muon backgrounds that are endemic. These two have already been addressed.

5.1. Background from Enshrouded Sources

We know of two potential sources of an enshrouded neutrino signal from the GC. One – neutrino production via high energy cosmic ray scattering on the ambient material in the Galactic plane – is virtually assured (Gaisser, Halzen & Stanev 1995; Ingelman & Thunman 1996). The other – neutrino production via annihilation of WIMPs accumulated in the gravitational well at the GC – is a possibility (Jungman, Kamionkowski & Griest 1996; Gondolo & Silk 1999).

5.1.1. Neutrino Production off the Interstellar Medium

Note that the first background source is, like the Sgr A East source, due to decay of pions produced in nucleon-proton scattering. The density of ambient matter in the galaxy is greatest, in general, in the Galactic plane and greatest of all at the GC so we may expect a large background neutrino flux from this direction. Of course, the pionic decay also leads to the production of γ's. That we consider this neutrino source enshrouded, then, is due to the relatively large angular resolution of the proposed neutrino telescopes; the neutrino telescopes see neutrinos from a much larger area of sky than the γ-defined size of Sgr A East.

Detailed estimates have been made of the rate of neutrino production by the interaction of cosmic rays with the interstellar medium (Ingelman & Thunman 1996). This neutrino

flux has been shown, however, to be below the atmospheric neutrino background for much of the energy range under consideration. Even given that the GC background exceeds the atmospheric one above $\sim 5 \times 10^{14}\ eV$, the background from 0.3° of sky (as relevant for ANTARES) is still considerably below the signal.

5.1.2. Neutrino Production from WIMP annihilation

The exact flavor composition of the neutrino flux generated by WIMP annihilation is model-dependent. It is conceivable, for instance, that a large ν_τ component might be present in this signal, if it exists at all. There is a fairly robust and model-independent upper bound to the WIMP mass of 300 TeV (Jungman, Kamionkowski & Griest 1996). Neutrinos generated in WIMP annihilation processes will have typically between one half to one third the WIMP rest mass energy (The ANATRES Collaboration 1999). We cannot, therefore, strictly rule out the possibility that the Sgr A East neutrino signal is polluted with neutrinos from WIMP annihilation. We do not consider this possibility in any detail, however, because, most reasonable WIMP candidates have maximum masses some orders of magnitude below this. The neutralino, for instance, cannot be more massive than $\sim 3\ TeV$ if it is to be a WIMP candidate (Jungman, Kamionkowski & Griest 1996). Neutrinos produced in its decay, therefore, can, at worst, be just below the energy cut-off of the part of the GC neutrino signal we are examining.

6. Conclusion

The GC neutrino source should produce an observable oscillation signature. The strongest evidence for such would take the form of a ν_τ flux attaining a significant fraction of the ν_μ flux from from this source. Such a ν_τ flux may be inferred from the double bang

signature at IceCube, the km^3 successor to the AMANDA telescope. Detector-specific simulations are required for a confident determination of whether the double bang event rate due to the GC will be statistically significant in the event that either of scenarios 2, 3 or 5 is correct, but preliminary calculations reveal that this event rate may be just at the threshold of detectability. Such simulations are also required to determine whether IceCube might see the GC ν_μ signal against the atmospheric *muon* background.

A deviation from the expected ν_μ flux determined from γ-ray observations of the GC is guaranteed for all neutrino oscillation scenarios identified. Observation of such deviation would, however, constitute more equivocal evidence for oscillation than a strong ν_τ signal because of uncertainties in the total expected neutrino flux calculated on the basis of γ-ray observations. Certainly, the value of α, the numerical power of the power-law proton spectrum at Sgr A East, would have to be further constrained before the above became a useful diagnostic (as would $\Phi_\nu(10\ GeV)$). The actual ν_μ flux should be able to be inferred from the ν_μ event rate experienced by a future, Mediterranean-based km^3 Čerenkov neutrino detector.

Strong confirmation of the oscillation signature will require observation of ν_e flux from the GC to see whether the ν_e to ν_μ ratio varies significantly from 1/2 (though, as discussed, if the small mixing angle solution to the solar neutrino problem is correct ν_e's will not oscillate on their way from the GC). The energetics of the GC 'beam', however, place it below the region where next-generation techniques and detectors are currently predicted to be able to identify a ν_e component. Such confirmation, then, must lie some decades into the future.

Perhaps the best science that might be extracted from the GC neutrino spectrum as observed by a future km^3 Čerenkov neutrino detector, assuming that other experiments resolve the electron- and muon-type neutrino oscillation mode questions first, is an empirical

determination of α. By such a determination, a neutrino telescope would realize the aspiration expressed in its very name, that, at base, it is a device for investigating the nature of astronomical objects, not merely the radiation they emit.[7]

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[7]A similar point is made by Raffelt (1998).

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